# WCAP-16996-P, "Realistic LOCA Evaluation Methodology Applied to the Full Spectrum of Break Sizes (FULL SPECTRUM LOCA Methodology)"

## Requests for Additional Information – (Non-Proprietary)

## RAI 45

**June 2013**

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## Question #45:

Please demonstrate that the assumption for the validity of Wilks Theorem holds with regard to the application of the code described in WCAP-16996-P/WCAP-16996-NP, Volumes I, II and III, Revision 0, in quantifying a single probabilistic statement of safety for the full spectrum of breaks, the full spectrum of model parameters and their variation, and the models of the engineered safety systems for small, intermediate and large break LOCAs. That is, there are no disjoint density functions of the figures of merit, or you can identify them and take them into account in the application of Wilks theorem.

**Response:**

## 1. Introduction

The issue raised with RAI-45 is broad and far reaching as it challenges the basis and best practices of approved best estimate LOCA methodologies as they are applied in the industry today (References 1, 2, 3, 4 and 6).

This request was motivated by the staff's concern that the FULL SPECTRUM™ LOCA (FSLOCA™)[1] Evaluation Model (EM) represents a "game changer" with respect to the method used to combine the uncertainties. It was pointed out that sampling uncertainties in this framework could lead to the "*the introduction of a continuous (rather than constant) parameter that can greatly alter in a discontinuous fashion the dynamics of the system. That is, there may appear multiple, stable, nonintersecting solutions, (i.e. bifurcations) that need to be taken into account in Wilks' theorem.*"

The intent of the FSLOCA methodology is <u>not</u> to provide a singular statement that applies to the full spectrum of breaks as stated in the question above but rather to [

]$^{a,c}$

In the ASTRUM Safety Evaluation Report (SER) (Reference 1), the staff judged a 95/95 statement on the figures of merit as acceptable [
]$^{a,c}$ The 95/95 criterion is also now de-facto a standard practice in the industry. [

]$^{a,c}$

Thus, if the question is limited to the possibility of generating disjoint density functions of Peak Cladding Temperature (PCT) [

]$^{a,c}$

In the following, the possibility of disjoint sets which may result from chaotic solutions will be discussed.

The intent here is to first define and clarify the problem statement such that Westinghouse can formally and logically address the reviewer's underlying concern. The response is constructed by following the steps below:

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1) Analyze the details of the question and restate the problem statement. Decompose the questions into elements that can be addressed in a logical and constructive manner (Section 2).

2) Define the scope and boundary of the questions within the envelope and purpose of the FSLOCA EM intended application, and consistent with 10 CFR 50.46 and applicable Regulatory Guides (RG 1.157 [23] and RG 1.203 [25]) (Section 3).

3) Address the question in each of the subtopics (Section 4).

## 2. Problem Statement Definition by Breaking Down RAI-45 into Elements

In order to facilitate the resolution of the issue, the RAI-45 question is broken down into four key elements. Westinghouse then provides a response to each element in Section 4. Here below are the elements:

**45.1.** Model and Input uncertainties are randomly sampled in the plant analysis following a direct Monte Carlo propagation of uncertainty method using a validated code. The code simulation of a particular scenario is expected to represent a random realization of the Pressurized Water Reactor (PWR) transient response to the postulated event. The effect of varying model parameters in the process is questioned. One difference between the plant simulation and the methods used to validate the code against Integral Effects Tests (IETs) is that model parameters are kept constant in the latter and varied in the former. In other words, in the current WCAP-16996-P [11], the adequacy of the validation is based upon comparing IET test predictions by the code with models set at their coded nominal values to IET test data. Typically the code is shown to be more conservative than the data with respect to key Figures of Merit (say PCT). **QUESTION: Can the same conclusions be supported accounting for the propagation of model and input uncertainties in the IET simulation?**

**45.2.** Sampling uncertainties in this framework could lead to the introduction of a continuous (rather than constant) parameter that could potentially alter in a discontinuous fashion the dynamics of the system. That is, there may appear multiple, stable, nonintersecting solutions, (i.e. bifurcations) that need to be taken into account in Wilks' theorem. **QUESTION: Are simulations of IETs affected by chaotic behaviors (bifurcations)? Can we still support a high probability statement that uncertainties are properly captured?**

**45.3.** Part 45.2 addresses the IETs. Plant analysis models consider additional uncertainties (Plant Design Parameters). The same question applies here. **QUESTION: Are simulations of PWRs affected by chaotic behaviors (bifurcations)? Can we still support a claim that there is a high probability that our sample includes a limiting transient which bounds the 95% of the population with 95% confidence?**

**45.4.** Addressing parts 45.2 and 45.3 explores the possibility of clustering solutions in disjoint, non-intersecting sets. Wilks' theorem (see Pal-Makai (2002) or Guba-Makai (2003), References 7 and 8) only requires the unknown cumulative distribution *G(y)* to be continuous (in our application *y* can be the PCT value from a simulated transient - max clad temperature in time and space). The continuity can be ensured by satisfying uniqueness of the solution for given initial and boundary condition. Uniqueness of the solution and Chaos are two different issues and this part of this response is intended to clarify and elaborate on this argument. **QUESTION: Assuming a degree of Chaotic variability (or volatility) is real and properly captured by the model, is it still possible to rely on Wilks' theorem (and order statistics) to infer an upper tolerance limit for the PCT/Maximum Local Oxidation (MLO) and demonstrate compliance with the 10 CFR 50.46 regulation?**

## 3. Assumptions and Regulatory Guide Compliance

The response is developed starting from some key premises:

1) Principles of Regulatory Guide 1.157 and 1.203 are followed.
2) This is an engineering solution to a complex theoretical question.
3) Precedence and validity of approved license applications in the industry is considered.

In discussions with the staff, the reviewer sees the FSLOCA methodology as a "game change".

However, in Westinghouse's view, [

]$^{a,c}$ Also, other vendors in the industry rely on similar approaches and similar computer codes architecture.

The new features in FSLOCA are predominantly [

]$^{a,c}$

The FSLOCA EM (WCAP-16996-P, Reference 11) employs [

]$^{a,c}$ This is consistent with Regulatory guide 1.157 which states that "*A 95% probability is considered acceptable to the NRC staff [...] to show that there is a high probability that the criteria [b.1 to b.3 of 10CFR50.46] will not be exceeded.*"

Westinghouse's intention is to address the issue stated in RAI-45 following the breakdown of the question suggested above (elements 45.1, 45.2, 45.3 and 45.4). However, in the resolution of these elements it will be assumed [

]$^{a,c}$

## 4. Response to the elements of the question 45.1, 45.2, 45.3 and 45.4

### Element 45.1

It is recognized that experiments (Separate Effects Tests (SETs) and IETs) used to validate the codes are representations of postulated events and potentially affected by distortions due to scaling biases or the limited number of tests. The fact that tools are validated by comparing code simulations to those individual tests has to be acknowledged. It is desirable to well-predict or to retain some degree of conservative biases in the code when assessing code predictions to IETs.

This is consistent with regulatory guidance. As stated in RG 1.157: "*...In practice, best-estimate codes may contain certain models that are simplified or that contain conservatism to some degree...*". And further "*The introduction of conservative bias or simplification in otherwise best-estimate codes should not, however, result in calculations that are unrealistic, that do not include important phenomena, or that contain bias and uncertainty that cannot be bounded. Therefore, any calculational procedure determined to be a best-estimate code in the context of this guide or for use under paragraph 50.46(a)(i) should be compared with applicable experimental data to ensure that the calculation of important phenomena is realistic.*"

The judgment on the adequacy of predicting IETs in the Topical Report (TR) (WCAP-16996-P) is based on setting the facility input model and code models at their best-estimate as-coded values, and simulating the test as it was executed to ensure that the key phenomena are properly accounted for. Section 24 of the TR also provides further analysis into the compensating errors to ensure that observed biases do not add undue distortion to the simulation.

Question 45.1 raises the issue if such adequate conclusions can be drawn after accounting for uncertainty propagation. If that is the case, then a similar argument can be extended to the plant analyses which do in fact consider propagation of all uncertainties.

To address the issue an analysis was conducted utilizing the CCTF-62 test. The CCTF-62 test is presented in Section 19.6 of the TR and is one of the key IETs utilized to demonstrate the code capabilities in modeling realistically the refill and reflood phases of a postulated LBLOCA in a PWR. The CCTF tests are the largest scale integral tests available to investigate these phenomena. CCTF has a flow area scaling of 1/21.4 of a four-loop PWR and includes a full-height (12 foot heated length) core section with three intact loops explicitly modeled. Its large scale makes the facility particularly well suited as verification of the code's ability to handle the multi-dimensional thermal hydraulics in the core. In addition, the full-height scaling makes these tests important indicators [ ]$^{a,c}$

As stated in Section 19 of the TR, WCOBRA/TRAC-TF2 was shown to [ ]$^{a,c}$ The important phenomena to be addressed by the CCTF 62 simulation are water accumulation in upper plenum, steam binding effect, and core quenching during gravity reflood.

From the code assessment (with the nominal model), the adequacy of the EM is based on demonstrating the following conclusions:

a. Important phenomena are adequately or conservatively predicted,

b. Any miss-predictions (or conservative predictions) are acceptable and explained, and

c. There is adequate evidence that when applied to the full scale PWR transient analysis of the same scenario, the EM is likely to produce reasonably accurate results.

d. The conservative nature of the EM enables one to conclude that the confidence on the predicted 95% PCT for the plant analysis is 95% or higher.

The results presented in the TR were obtained with the code models at their nominal, as-coded settings and the question here is if same conclusions can be reached when uncertainties are ranged. The purpose of the analysis presented in this response is to demonstrate that this is the case. Preliminary results (fully documented herein) were already presented to the Staff in August 2012 for the purpose of addressing this part of the issue (Reference 12).

The following exercise was conducted:

- Code model parameters whose ranging may impact the prediction of CCTF data were identified.
- Uncertainties in test initial and boundary conditions were characterized.
- A random sample of simulations [ ]$^{a,c}$ was obtained, where uncertainties were sampled similarly to the procedure used in plant analysis.

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[2] There is nothing specific to [ ]$^{a,c}$ as described in the Topical Report (WCAP-16996-P).

- Code model ranging was based on the SET assessment and the sampling procedure is consistent to what would be followed in a plant analysis. Models include [

  ]$^{a,c}$

Initial and boundary conditions uncertainties were extracted from the test report (Reference 13) and sampled in the analysis. For example the initial temperature of the accumulator water was reported to be affected by uncertainty of +/- 1.5%. This uncertainty range was used as a basis for the sampling. The results of these [ ]$^{a,c}$ Monte Carlo simulations are discussed in the following.

Figure 1 shows the PCT(t) traces for [ ]$^{a,c}$. Figures 2, 3 and 4 shows the following curves for all the three elevations in the bundle respectively (6.0, 8.0 and 10.0 ft):

- [

  ]$^{a,c}$

Figures 2, 3 and 4 show [

]$^{a,c}$

Figures 5, 6 and 7 show respectively [

]$^{a,c}$

In conclusion these results address issue 45.1.

a,c

Figure 1 – [ ]$^{a,c}$

a,c

Figure 2 – Predicted [

]$^{a,c}$

a,c

Figure 3 - Predicted [

]$^{a,c}$

a,c

Figure 4 - Predicted [ ]$^{a,c}$

[ ]a,c

Figure 5 - Predicted [ ]a,c

a,c

Figure 6 - Predicted [ ]$^{a,c}$

a,c

Figure 7 - Predicted [ ]$^{a,c}$

a,c

Figure 8 – [ ]$^{a,c}$

**Element 45.2**

The previous results were inspected to identify possible chaotic behavior which could arise by varying model parameters as stated in the question. For this set of IET simulations [ ]$^{a,c}$ not exceeding the acceptance criteria as stipulated in the 10 CFR 50.46 regulation.

**Element 45.3**

CCTF-62 is intended to represent the PWR behavior (refill and reflood phases) in response to a large break LOCA event. For the PWR analysis the same approach is followed. However, note that while in a test (like CCTF) the initial and boundary conditions are quite controlled, for the plant analysis the number of parameters sampled is large and ranges are wider to reflect possible plant operating ranges [ ]$^{a,c}$

Figure 9 shows [

]$^{a,c}$ not exceeding the acceptance criteria as stipulated in the 10 CFR 50.46 regulation.

a,c

Figure 9 – [

]$^{a,c}$

Chaotic behaviors in the classical sense, i.e. high sensitivity to small perturbation to inputs, are a physical expectation in some cases. For example the interaction between system wide phenomena such as random loop seal clearing, venting capability and core level depression, etc. may lead to bifurcating events. These phenomena were observed and analyzed in response to RAI-9 and RAI-12.

In order to explore this further **[**

]$^{a,c}$ The description and purpose of each study is presented next.

**Study 1 (S1)**

Description: This is [

]$^{a,c}$

Purpose: Identify if [

]$^{a,c}$

**Study 2 (S2)**

Description: This is a repeat of S1 with [

]$^{a,c}$

Purpose: Assess the impact of [

]$^{a,c}$

**Analysis of the PWR Studies (Studies S1 and S2)**

Figure 10 shows [

]$^{a,c}$

a,c

Figure 10 – [ ]a,c

Figure 11 shows [ ]a,c

a,c

Figure 11 – [ ]$^{a,c}$

Figure 12 shows [

]$^{a,c}$

Figures 13 through 16 show [

]$^{a,c}$

The concern with a chaotic solution is sometimes explained as the "volatility" in the solution, borrowing a term from the financial market. In other words, the concern is that a possible solution branch could be quite more severe than the solution in another more nominal branch. The distance between the solution disjoint sets could be a concern. A large distance between the sets casts some doubt on the sample size because of the possibility of missing some of those unlikely but very severe events. These studies shows [

]$^{a,c}$

a,c

Figure 12 – [ ]a,c

a,c

Figure 13 – [ ]$^{a,c}$

a,c

Figure 14 – [ ]$^{a,c}$

a,c

Figure 15 – [ ]$^{a,c}$

[ ]a,c

Figure 16 – [ ]a,c

Figure 17 shows [

]$^{a,c}$

a,c

Figure 17 – [ ]$^{a,c}$

**Conclusions from the PWR Studies**

The following conclusions are drawn from the previous analysis:

- The code [

]$^{a,c}$

## Element 45.4

It is recognized that the problem at hand is complex and non-linear in nature. Non-linear operators are known to exhibit chaotic behaviors. The work performed as part of 45.1 to 45.3 addresses the issue on the code applicability and capability to model such behaviors.

However the reviewer challenges the applicability of Wilks' theorem in the case that chaotic behaviors are possible in the plant. Similarly the Pal, Makai and Guba literature deals with the possibility of chaotic behavior of output variables which is observed in some computer simulations and poses the same questions.

There are two parts to this response. The first is to restate the problem by clarifying that for the LOCA safety analysis [

]$^{a,c}$ The second part is to reflect on the mathematical assumptions which are actually at the basis of the Wilks' theorem. Review of pertinent literature shows [

]$^{a,c}$ and the response will elaborate on these points.

The current practice in the industry to meet the NRC requirements in achieving the high level of probability required by the 10 CFR 50.46 rule is to bound 95% of the population of PCT and oxidation with 95% confidence. The procedure is a Monte Carlo sampling of the uncertainty attributes and the generation of a sample of scenarios from a hypothetical population of them. From each simulated transient in the sample specific figures of merits such as maximum clad temperature and oxidation are tallied.

The thermal-hydraulic computer code designed to simulate the transient is what the Guba-Makai-Pal (GMP) paper refers to as the 'black-box'. In this case the back box receives as input a set of random values, one for each uncertainty parameter, and outputs the selected figures of merit (PCT and oxidation). [

]$^{a,c}$ The issue here is how the results are interpreted to demonstrate compliance with 10 CFR 50.46 requirements.

The currently approved LBLOCA methodology (ASTRUM) relies on a non-parametric order statistics procedure with a minimum sample size. The results are ranked and the top rank is selected as the estimator. [

]$^{a,c}$

Now, it is important to recognize that the only mathematical requirement for the applicability of the method is shown in the footnote of pg. 224 of GMP (2003) [8]: "The probability that equal values occur is zero" – i.e. a continuous CDF of the output.

The implementation of non-parametric techniques in the framework of LOCA safety analysis generated a vigorous debate in the industry in the previous decade [References 14 to 22]. Much of the debate in the early 2000's was given to the 'sample size problem', since most of the vendors were utilizing maximum order statistics estimators with small sample size (<150 cases) to infer upper tolerance limits. This issue is today much less important since computational capabilities allow larger sample sizes at reduced costs.

Instead the emphasis in RAI-45 is on more fundamental questions associated with the 'mathematics' and the fidelity of the computer codes used to analyze these complex scenarios [24], [25].

It is recognized that the problem at hand is complex and non-linear in nature. Non-linear operators are known to exhibit chaotic behavior. Section 4 of Guba-Makai-Pal (2003) deals with possibility of chaotic behavior of output variables and observed in some computer simulations. More specifically Section 5 of GMP (2003) states that "*...we assume that the observed randomness of output variables is the result of the randomness of input variables, and the mapping y(X)=C(t) X does not show chaotic behavior...*"

GMP (2003) continues by providing stringent requirements for safety:

- *A state **x** is called safe if **y** is in the safety envelope for every x in [X], where [X] is the set of all possible values of x.*
- *If there is a value outside the safety envelope the state is unsafe independently of the fact that the nominal state may be safe.*

Obviously the above statement appears to point to the population of events and an ideal solution which aims in determining the safety of a design in a deterministic sense, i.e. 100% probability. In practice the requirements are different, because an engineering safety statement is made assuming some risk. For instance, the 50.46 regulation requires that there is a very low probability of falling outside the safety envelope (not "a value" as stated – i.e. zero probability).

The problems of bifurcation and cliff effects are also discussed by D'Auria (2000) (Reference 26). Their paper provides a good classification by distinguishing between bifurcations originated by the safeguard system (actuation of valves for example) and bifurcations originated by phenomena, which possibly are the ones to which the GMP work refers. Note that a combination of the two causes is also possible.

In other words it is reasonable to speculate about the existence of phenomena-driven bifurcation during a postulated (and simulated) LOCA event. However, we should differentiate true chaotic behaviors from threshold effects, like the occurrence of burst and swelling which may lead to a different scenario as far as the clad heat up and oxidation transient are concerned local to the burst region; or the occurrence of dryout which determines the clad temperature excursion.

On the other hand phenomena such as [
]$^{a,c}$ are rather chaotic and may lead to chaotic behaviors, or high sensitivity to small variation in the inputs according to the classic definition of Chaos. D'Auria (2000) concluded that phenomena-based bifurcations are implicitly accounted for in their method. Similarly Makai-Pal (2003) show that chaos in output may be predicted by thermal-hydraulic system codes (ATHLET in this case).

This leads to the conclusion that as long as the physics are properly modeled in the system code of choice, chaotic events are predicted and eventually captured in the uncertainty methodology which typically exercises the solution with random sampled inputs as discussed in the previous section.

The presence of disjoint-set data structures does not prevent the use of the Wilks' theorem which is simply a tool to infer a probabilistic statement from a sample of the population. The issue of having disjoint sets in itself does not prevent the applicability of non-parametric statistics, as long as the solution is unique. Order statistics only requires the CDF of the population to be continuous (References 8, 9 and 10) which can still be achieved even in the case of disjoint sets. As long as the population underneath a disjoint set (or multiple attractors) is sampled by the code by randomly sampling the inputs, disjoint sets and unlikely scenarios will be considered to the extent of their probability weight. Note that when dealing with computer codes the uniqueness of the solution is not violated, i.e. for exactly the same input, the same output is reproduced.

Sometimes large sensitivities to small perturbation of the inputs are claimed for some parameters like the level in the downcomer (per Reference 8). However for the purpose of safety inference it is more appropriate to examine the effect on figures of merit (outputs) that more directly relate to the 10 CFR 50.46 criteria, PCT for instance. Therefore, the conclusions in Reference 8 which describe clustering of predicted transient level in the downcomer may not be fully relevant in judging the impact on the PCT solution.

Ultimately, rather than challenging the applicability of the Wilks' theorem for the inference of the statistical measure in such a context, the issue should reside on the degree of belief that the simulation run-set sample represents with high fidelity an unknown population of 'real' PWR transient evolutions, once parameters are varied according to the sampling procedure. The work performed as part of this response and the observations from other authors (e.g. Reference 8) provide reassurance on the predictability of such behaviors and, once they are predicted, the extent of the chaotic volatility of the solution.

Finally, it has to be recognized that a mathematical proof or certainty with respect of the fidelity issue is unattainable given the complexity of the problem and the tools used to analyze the problem. The acceptability of the method resides in the realm of a reasonable demonstration that the code simulations are a good representation of the possible real scenarios. This will ultimately lead to the engineering judgment that the design is safe within tolerances that satisfy the intent of the 10 CR 50.46 regulation.

Such reasonable demonstration can be drawn primarily from the code V&V against SETs and IETs provided in Volume 2 of the TR, and complemented by the studies presented in this response.

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